

Reliable monitoring of hostile, spatial events with Wireless Sensor Networks

Design and verification of resilient,
environment-aware, multipath routing protocols

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1 Introduction

The direct and indirect effects of industrial activity have become tangible over the last few decades. Phenomena caused by climate change, such as wildfires, flash floods, and landslides regularly affect the environment. Industrial disasters, in particular oil spills, toxic pollutions, and plant accidents, occur frequently and have a devastating impact on human lives, nature, and built infrastructure. Timely detection of such hostile phenomena supports the prevention, defense, mitigation, and recovery from hazards, which can save lives and the environment.

The continuous advancements in wireless communication, computing, sensing, and energy-storage technologies have made possible the invention of wireless sensor networks (WSNs). A WSN comprises independent, autonomous sensing devices, known as nodes, that communicate over wireless media and possess an infrastructure-independent energy source. WSN nodes are deployed over an extended area, while sensor information is aggregated for further usage by one or more distinctive nodes, called a sink. Due to its sensing capabilities, distributed architecture, and infrastructure independence, WSNs are particularly suitable for monitoring hostile phenomena with spatial extent.

Information delivery in a WSN is a non-trivial task. Due to the network's spatial topology, the majority of the nodes have no direct connection to the sink. To successfully aggregate information of each device, individual WSN nodes must accept information from neighbors and forward it towards the sink via a specific path, that is, perform routing. The rules that describe the related actions are known as the routing protocol. Throughout the WSN's operation, certain devices can fail due to depletion and attrition, whereas during hostile events, multiple nodes can be damaged at once. Such failures can disconnect parts of the network, preventing the WSN from reliable operation. Various techniques can be employed to prevent and mitigate such scenarios, such as establishing various independent paths, deploying multiple sinks, or utilizing environment, network, and energy information to achieve reliable and resilient routing, prolong network lifetime, and maintain the network's sensing capabilities. In the presence of a hostile event, a WSN's lifetime can be extended further by avoiding damage via mobility. However, node locomotion can have adverse effects without appropriate routing support, similar to failures.

In this booklet, I present theses proposing state-of-the-art routing protocols that support single- and multi-sink WSN deployments with optional mobility and employ various techniques to provide reliable and resilient information delivery. Furthermore, I present models for hostile phenomena, sensing, and mobility, along with various metrics to assess routing protocol performance in area monitoring.

2 Wireless Sensor Networks

WSNs provide a ground-based, distributed remote sensing approach: WSN devices, also known as nodes, are deployed over the region of interest (ROI), and can operate autonomously. These devices, shown in Figure 1, are self-contained, that is, they possess an energy source, sensors, and wireless communication capabilities, thus do not depend on infrastructure and can perform monitoring for a sustained period of time without significant delay. WSN nodes are relatively affordable; therefore, the network's sensing precision and coverage can be increased by adding new components to the network. Furthermore, WSNs can monitor complex terrains even with limited line-of-sight (LOS) coverage, where other remote sensing technologies would fail. Additionally, WSNs' capability to perform locomotion can further extend precision and coverage, and adapt to environmental changes. These properties make WSNs particularly suitable for environmental monitoring, especially in the case of hostile events. In terms of costs, WSNs provide a feasible alternative not just to satellites or airborne platforms, but also to ground-deployed, wired systems, as shown by Silvani and Peres [1].

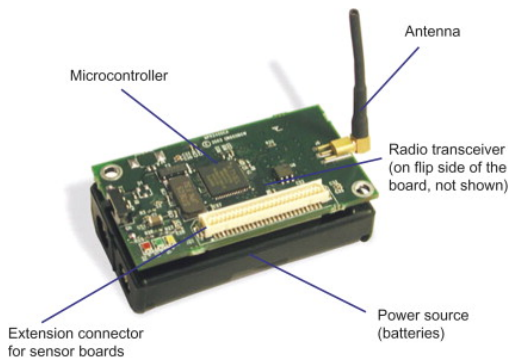


Figure 1: The Mica-Z WSN node with major components labelled.

Exploiting the monitoring capabilities of a WSN to their full potential is a non-trivial task. Sensor information must be delivered to one or more distinguished WSN nodes, called a sink. Since a WSN is geographically distributed, not all devices are directly connected to a sink; thus, information delivery must be realized via hop-by-hop transfer between WSN nodes. This activity is also known as routing, whereas the set of rules that coordinate the WSN is called the routing protocol and is essential from the WSN point of view. Successful information delivery can be hindered by node failures, disruptive events, varying communication conditions, and changes in network topology, which a suitable routing protocol must handle and mitigate.

3 Areas of investigation

Monitoring spatially extended hostile events with WSN imposes specific requirements on the routing protocol. Nodes exposed to such an event can fail, rendering parts of the network disconnected, whereas the most valuable information is generated by devices in the vicinity of the event. Means, such as multiple paths and sinks and mobile nodes, can enhance the network's monitoring capabilities; however, these cannot be properly utilized without appropriate routing support. During my research, I investigated different aspects of WSNs utilized for hazardous event monitoring. Independent of the particular event, requirements that stem from the application of WSN to perform unattended event monitoring bear numerous similarities. Such requirements relate to resilience, energy efficiency, or reliability. To provide a realistic context and boundaries for the presented routing protocols, wildfire was chosen as the hostile event.

3.1 Multipath routing

Nodes in a WSN network that cover a spatially extended area do not have a direct connection to the sink. Multi-hop communication is required to convey information from a distant node, which defines a sequence of nodes, also known as a path, via which messages can be transmitted to the sink [2]. Every path is vulnerable to node failures, rendering the given node disconnected. A commonly used technique to enhance a multi-hop WSN's reliability is establishing multiple paths towards the sink to increase the connection redundancy available to a node [3]. Depending on the structure of the constructed paths available to a node, it is possible to classify multipath networks further, as depicted in Figure 2.

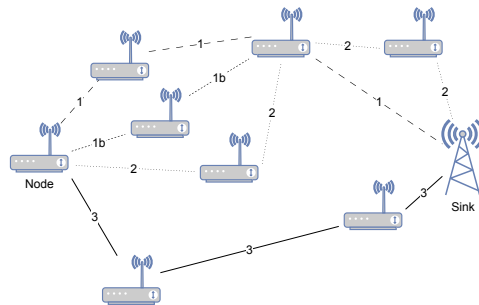


Figure 2: Multipath scenarios between Node and Sink: node-disjoint (1,3), link-disjoint (1,2), and partially disjoint (1,1b) paths.

3.2 Environment-aware protocols

WSNs are designed to observe physical events occurring in the monitored spatial area. If the sensed event is hazardous and destructive, the occurrence is fatal to the sensing node and can cause a network outage due to the loss of an intermediate node along one or more paths. Environment and context-aware routing protocols utilize sensor information to construct a network and perform routing, enabling them to mitigate node losses caused by hazardous events and prepare the network for such situations proactively.

3.3 Multipath and multi-sink routing protocols

Exploiting the multi-node property of WSNs to increase reliable information delivery is a constant focus of researchers when developing corresponding routing protocols. Multi-sink WSN architecture and routing have also been investigated since the inception of WSNs. In such WSNs, each node can connect to various sinks present in the network. Although multipath and multi-sink approaches can increase the WSN's network performance, resiliency, and lifetime [4], relatively few routing protocol-related works have investigated their joint application.

3.4 Limited mobility

Mobile WSNs (MWSN) have been researched from various aspects over the past two decades. Studies have been conducted in connection with mobility on network lifetime [5], monitoring efficiency [6], [7], medium access control (MAC) protocols [8], and routing [9]. Considering the environmental, technological, and economic aspects of hostile event monitoring, only nodes with limited mobility capabilities can be considered feasible. Whereas prior works thoroughly studied limited mobility to increase MWSN's coverage capabilities, no work investigated the mobility concept in the context of hostile, destructive event monitoring. Moreover, neither of the works provided a corresponding routing algorithm that would support topology changes due to mobility.

3.5 Conclusion

Literature review revealed that environment-aware multipath routing protocols published until now have failed to address every aspect of hazardous event monitoring, while they missed performing measurements, where the monitored physical process evolves spatially over time. By addressing the recognized gaps and by collecting and synthesizing the requirements from previous works related to a routing protocol that supports a WSN deployment for hazardous event monitoring, various items have been identified related to network organization, maintenance, resiliency, and failure tolerance. An extended literature review suggests that contemporary routing protocols fail to exploit the aforementioned capabilities in combination.

In the presence of multiple sinks, further enhancement of WSN's performance can be achieved with multipath and multi-sink routing protocols. Although the covered works apply these concepts, they do not utilize link-specific information, provide a local failover mechanism, or evaluate the effects of mobility.

Works related to limited mobility in WSNs focus on problems associated with coverage. None of the works studies mobility concepts related to hostile event monitoring and adaptation. Moreover, none of the reviewed studies investigates routing-related issues in MWSNs.

4 Methods of investigation

An extensive literature review was performed to investigate WSN-related routing protocols with environment-aware, multipath, multi-sink, and limited mobility capabilities suitable for hostile event monitoring. Review findings were published with the corresponding protocol work [J1], [J2], [J3]. Based on the findings, requirements for routing protocols employed in WSN networks were compiled.

Actual protocol design and development were initially built on the results of wildfire monitoring [10], which suggested the Heterogeneous Disjoint Multipath Routing Protocol (HDMRP) proposed by Hadjidj *et al.* [11] as a feasible routing protocol. Incorporating environment-aware, link measurement, and failover capabilities, a new protocol was proposed, entitled Resilient Reliable Multipath Routing Protocol (R2MRP). R2MRP, along with benchmark protocols restricted broadcast, HDMRP, and Environment-Fusion Multipath Routing Protocol (EFMRP) [12] was implemented utilizing the OMNeT++ simulation environment [13], and the WSN-specific Castalia framework [14]. Various simulation measurements were performed related to network performance, energy efficiency, and resiliency. Furthermore, a cellular-automaton wildfire model proposed by Alexandridis *et al.* [15] was also implemented, accompanied by a new sensing model with spatial capabilities to evaluate protocol behavior during hostile events.

The manuscript encompassing the proposed protocol, the sensing model, the retrieved simulation results, and the corresponding literature review of multipath and environment-aware protocols was published [J2], along with the corresponding source code [O1].

Building upon the results of R2MRP, three main areas of further research were identified: a) multi-sink network architectures, b) utilization of multi-criteria decision analysis (MCDA) techniques during routing, and c) impact of limited mobility on network resiliency and monitoring capabilities. Based on the findings of the concluded literature review, expanding the capabilities of R2MRP, the Multi-sink Resilient Reliable Multipath Routing Protocol (MsR2MRP) was proposed. The protocol possesses capabilities to exploit a multi-sink WSN, and utilizes the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) MCDA method [16]. Furthermore, in cooperation with the application layer, it is capable of assisting locomotion performed by individual

WSN nodes. To evaluate the protocol’s performance, resiliency, and energy-efficiency capabilities, intensive simulation measurements were performed. To serve the computational needs of simulations, the measurement environment was adapted to meet high-performance computing (HPC) requirements, whereas the measurements were performed on the Komondor HPC system [17]. In addition, the protocol was benchmarked against the Sustainable Multipath Routing Protocol (SMRP), a state-of-the-art routing protocol, possessing similar capabilities [12]. A limited-mobility model was also proposed to simulate node locomotion. Both protocols were evaluated in normal operating conditions, performing limited mobility, and in the presence of hostile events. To assess MsR2MRP’s disjoint multipath and resiliency capabilities, new metrics were proposed.

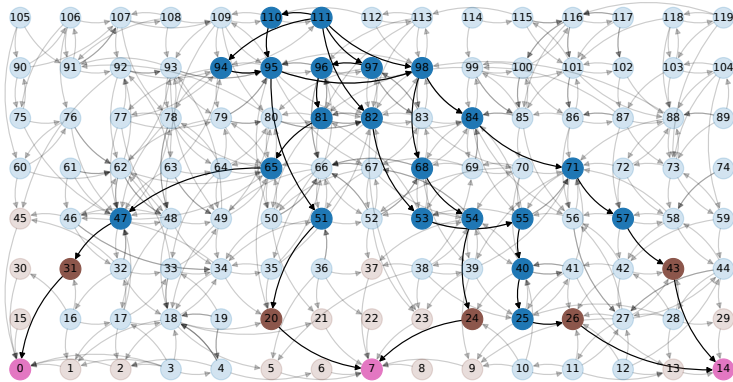


Figure 3: Logical topology constructed by MsR2MRP. Sink nodes are indicated with purple, border nodes with brown, and sensor nodes with blue.

The manuscript detailing the proposed protocol, the mobility model, the metrics, and the retrieved simulation results, accompanied by the literature review on multipath and multi-sink routing and limited mobility, was published [J3], whereas the corresponding source code was also made public [O2].

5 New scientific results

Thesis I. *I proposed a resilient, reliable, environment-aware, multipath routing protocol for WSNs, entitled R2MRP, suitable for area monitoring with hostile events. The protocol utilizes environment, link, and energy information to construct a node-disjoint network. Furthermore, in cooperation with the application, the protocol is capable of adapting to node failures and the presence of hostile events to ensure uninterrupted information delivery. I compared the proposed R2MRP with state-of-the-art routing protocols known from the literature, such*

as EFMRP and HDMRP. Via simulation measurements, I showed that R2MRP outperforms benchmark protocols in terms of energy efficiency and reliability by 10% and 30%, respectively.

Publications related to the thesis: [J2], [O1]

Compared to other protocols known from the literature, the R2MRP utilizes various information during network construction. These data are evaluated during path construction by each node in the network to ensure an energy-efficient and reliable network. The measurement related to energy usage depicted in Figure 4 shows that R2MRP is able to deliver at least 10% improvement in the energy per message metric, compared to HDMRP, EFMRP, and Restricted Broadcast measured within the same environment. The results show that R2MRP is able to construct a network in which message delivery consumes significantly less energy compared to benchmark protocols.

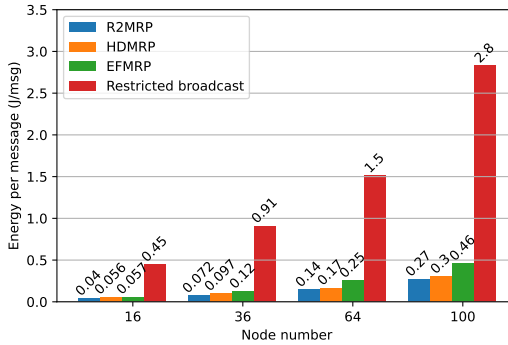


Figure 4: Energy spent by routing protocols to successfully deliver a single message in case of different node numbers.

Reliability is measured as the network performance of affected nodes during the failure of neighboring nodes due to a wildfire. In this case, R2MRP is able to outperform each aforementioned protocol in packet delivery ratio, at least by 30%, as shown in Figure 5. The results indicate that R2MRP successfully adapts to node failures caused by hostile events and assesses environment information during reorganization, providing resilient monitoring capabilities.

Thesis II. *I proposed a reliable, resilient, energy and environment-aware, multipath, and multi-sink routing protocol for WSN, entitled MsR2MRP, that supports node mobility and performs load balancing via a ranking algorithm. The protocol builds on the foundations of Thesis I and constructs an independent subnetwork for each sink present in the WSN. Furthermore, the protocol is capable of assisting nodes that perform mobility, that is, removing and reintegrating nodes, while maintaining the network's consistency. Regarding information*

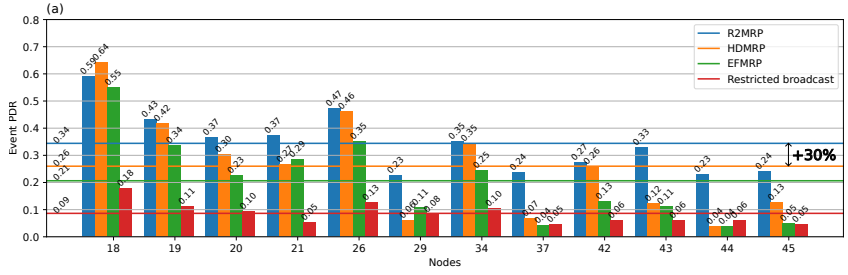


Figure 5: Routing protocol performance during hazardous event: (a) node-wise and average PDR, (b) percentage difference compared to normal operation.

delivery, the protocol performs load balancing across multiple sinks and multiple paths, utilizing the TOPSIS algorithm. I compared the proposed MsR2MRP with the state-of-the-art SMRP via simulation measurements. I showed that MsR2MRP outperforms SMRP in terms of network performance and resiliency by up to 69% and 25%, respectively.

Publications related to the thesis: [J3], [O2]

Similar to R2MRP, MsR2MRP is also an environment-aware, multipath routing protocol. Whereas the support for multiple sinks increases the connection redundancy of each node, the TOPSIS algorithm exploits the possibilities of a multipath and multi-sink network during routing. As shown in Figure 6a, MsR2MRP is able to outperform SMRP without the application of load balancing. However, if TOPSIS is enabled with flat weights (FW) or energy preferred (EP) options, MsR2MRP delivers up to 69% higher PDR on average, compared to SMRP, illustrated in Figure 6b and Figure 6c.

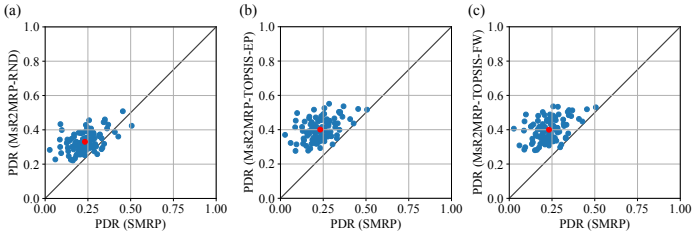


Figure 6: Comparison of PDR results of SMRP and MsR2MRP variants: (a) Random, (b) TOPSIS-FW, and (c) TOPSIS-EP method. Blue markers denote individual simulation results; red markers denote the overall average.

In the case of a hostile event that gradually destroys the WSN, it becomes utmost important to adapt to the changing environment. As shown by the results in Figure 7, a WSN with mobility support (MS) that utilizes MsR2MRP and corresponding routing support (RS) for mobility outperforms SMRP with similar capabilities, reaching a 25% difference in terms of nodes that are considered reachable in the network.

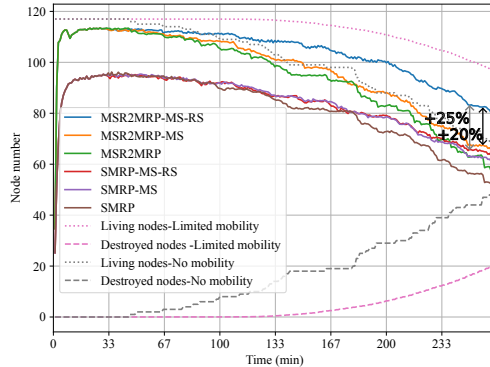


Figure 7: The number of living, dead, and reachable nodes over time in the case of a wildfire event. MS denotes mobility support of the WSN, while RS denotes routing support of mobility by the protocol.

Subthesis II.1. *I proposed a subnetwork-based, multi-sink extension of Thesis I. The resulting protocol constructs an independently manageable subnetwork for each sink in the WSN. The method enables a dynamic, on-demand, and concurrent management of a multi-sink WSN and increases resiliency and redundancy of network connections. Via results retrieved from simulation measurements, I showed that with the increase of sinks present in the network, the available paths and their pair-wise disjointness also increase.*

MsR2MRP does not actively maintain disjointness between paths that are associated with different sinks. This relief of constraint enables a significantly less complex protocol that is able to concurrently manage subnetworks. As the results retrieved from a 255-node WSN in Figure 8 show, the average available paths to a node increase with the number of sinks available in the network.

Whereas the number of available paths indicates resiliency, their disjointness is equally important. Results depicted in Figure 8 also show that with the increase of available sinks in the network, the probability of disjoint paths of the same number also increases. The result shows that path disjointness can be achieved in a multi-sink WSN without active maintenance, increasing the network’s resiliency.

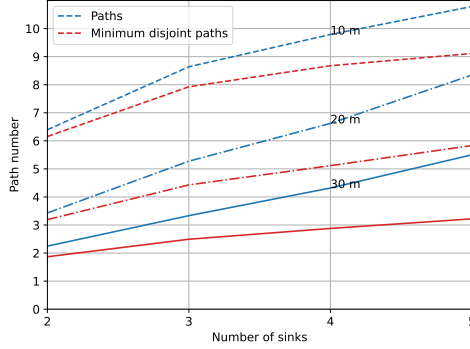


Figure 8: Average number of paths and average number of disjoint paths versus the number of sinks present in the network, in case of different node distances.

Subthesis II.2. *I proposed an application-driven limited-mobility support extension of Subthesis II.1. The method enables the routing protocol to allow individual nodes to perform locomotion while minimizing disruption in any subnetwork by proactively reorganizing the affected subnetwork. Furthermore, the method enables mobile nodes to attach to available subnetworks upon completion of the locomotion. Via simulation measurements, I showed that utilizing mobility information during routing and network reorganization increases the network's performance up to 20%.*

In the case of application-driven limited mobility, the task of the node's application is to detect the environmental condition, which makes it necessary to perform locomotion in order to protect the affected node from damage. This logic is realized by the finite state machine, shown in Figure 9.

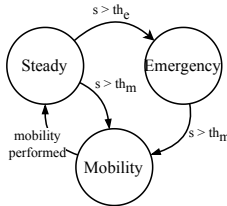


Figure 9: Application module's finite state machine. Term s denotes sensor reading, th_e denotes emergency threshold, and th_m denotes mobility threshold.

Prior to the locomotion, the application layer instructs the routing layer

to perform preparation, whereas upon completion of the locomotion, another explicit instruction is sent to the routing layer to perform reintegration into the network.

The results in Figure 7 show that in the presence of a hostile phenomenon, MsR2MRP with mobility support (MsR2MRP-MS-RS) outperforms the MsR2MRP variant lacking the capability (MsR2MRP-MS) in terms of network performance. With the time-wise progress of the phenomena, the difference in reachable nodes between the two variants reaches 20%.

Subthesis II.3. *I proposed a ranking-algorithm-based path selection mechanism for the routing protocol in Subthesis II.1. The method utilizes the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) algorithm to select an optimal path available to the WSN node for information delivery. The algorithm evaluates environment, energy, and network properties during decision-making. Additionally, the same method is utilized during subnetwork construction to increase network resiliency. I evaluated the proposed mechanism via simulation measurements related to energy efficiency. I showed that by applying the mechanism during route selection, 11% improvement can be achieved in the case of network performance and 21% in the case of energy efficiency, respectively.*

The TOPSIS algorithm evaluates the different attributes prior to sending a message from the originating node to a sink. Since certain attribute values dynamically change over time, repeatedly performing the calculation yields adaptation to a changing environment. Concerning network performance, measured as the average packet delivery ratio in the network, results depicted in Figure 6 show that with the application of TOPSIS, a 11% increase can be achieved compared to the MsR2MRP variant, where paths are selected with uniform distribution.

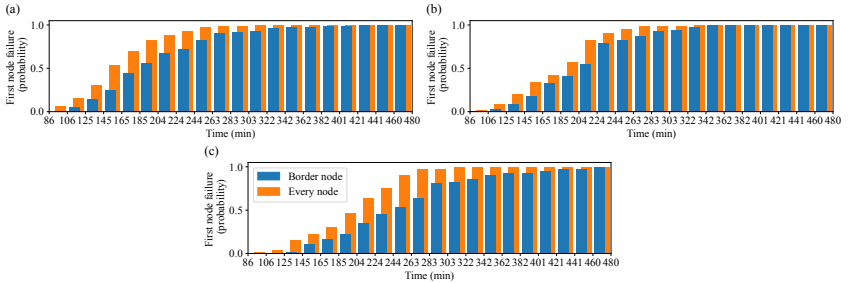


Figure 10: The cumulative distribution function of the first node and first border node failure: (a) Random, (b) TOPSIS-FW, and (c) TOPSIS-EP method.

In the case of energy efficiency, results are calculated as the probability of the first node failure in the network. The results in Figure 10a and Figure 10b

show that the time-wise probability of the first node failure exceeding 50% is achieved after 185 min, if TOPSIS is not employed; however, if TOPSIS is utilized with energy-preferred configuration (TOPSIS-EP), 224 min, that is, 21% more time passes to reach the same probability.

Thesis III. *I proposed models and metrics suitable to provide an evaluation environment for, and assess the capabilities of environment-aware WSN routing protocols. The proposed items are: a) a contemporary wildfire model extended with fuel moisture property, b) a spatial-capable sensing model, c) an integration of the wildfire model and the sensing model, d) a probabilistic mobility model, e) a metric to assess multi-path networks, and f) a metric to assess monitoring capability. I showed the effect of the models on the measured protocol aspects via simulation, and compared proposed items with contemporaries, where applicable.*

Publications related to this thesis: [J3] [O2] [C1]

The evaluation environment incorporates the OMNeT++ simulation engine [13] and the WSN-specific Castalia framework [14]. Whereas these components provide a versatile basis to evaluate WSN-specific communication protocols and concepts, they provide a sensing model and a mobility model with modest capabilities, and do not incorporate a model of spatially evolving hostile phenomena. To address these gaps and to provide a trustworthy environment to evaluate environment-aware routing protocols designed to monitor hostile events, a sensing model with spatial capabilities, a mobility model for limited-mobility scenarios, and an enhanced wildfire model were also proposed. The aforementioned components were made publicly available for further research [O2]. Furthermore, metrics were also proposed to assess generic and class-specific properties.

Subthesis III.1. *I proposed a sensing model that utilizes spatial environment information to provide sensor readings to the WSN application. The model evaluates environmental information relevant to the sensor, performs distance-based weighting and assesses the sensed phenomenon's spatial extent. Via simulation measurements, I showed that environment-aware routing protocols achieve more than 3% higher packet delivery ratio with the proposed sensing model, compared to other models known from the literature.*

Based on the literature review on sensing models and environment-aware protocols, it was concluded that the majority of the published sensing models consider only point-like events, whereas protocols utilize simplistic sensing models, even in the case of events with spatial extent, as shown in Table 1.

To cover the revealed gap in sensing models, the Spatial Sensing Model was proposed. The model assumes that the monitored area consists of cells of

Table 1: Sensing models and sensing distances in different routing- and scheduling-related protocol works. Attributes determined with inference, rather than by explicit data, are marked with *.

Reference	Year	Protocol name	Protocol type	Sensing distance	Sensing model
[18]	2009	EMA	Routing	100-200 m	Linear Disk Model
[12]	2020	EFMRP	Routing	N/A	Linear Disk Model*
[19]	2021	SMRP	Routing	N/A	Linear Disk Model*
[20]	2020	E3AF	Routing	N/A	Linear Disk Model*
[21]	2023	MS-E3AF	Routing	N/A	Linear Disk Model*
[22]	2017	LDG	Routing	25 m	Boolean Disk Model*
[23]	2012	MUP	Routing	N/A	Linear Disk Model*
[24]	2022	EAT	Routing	N/A	N/A
[25]	2022	ASSR	Scheduling	5-60 m	Boolean Disk Model
[26]	2006	DEEPS	Scheduling	10 m	Boolean Disk Model
[27]	2015	DiLCO	Scheduling	5 m	Boolean Disk Model
[28]	2006	N/A	Scheduling	5-30 m	Boolean Disk Model*
[29]	2011	LAR	Scheduling	6-15 m	Boolean Disk Model*

arbitrary precision:

$$f_s(x) = \begin{cases} \min \left(\sum_{b \in \mathbb{B}_x} \frac{1}{d(x, b)^a}, c_{max} \right), & \text{if } x \notin \mathbb{B}_x \\ c_{max} & \text{if } x \in \mathbb{B}_x. \end{cases} \quad (1)$$

In (1), f_s is the sensor reading function; x is the sensor node's position; $\mathbb{B}_x$ is the set of positions of burning cells within the predefined distance of the node; b is the general burning cell position; $d(\cdot)$ is the Euclidean distance function; a is the simulation level attenuation parameter; and c_{max} is the maximum sensor reading value. In case of 1 meter precision, the f_s takes values from the interval $[0, 8]$, and also c_{max} is set to 8.

Concerning the effect of the sensing model on environment-aware routing protocols, MsR2MRP achieves more than 3% increase in PDR compared to the Boolean Disk Model, and more than 1.7% increase compared to the Linear Disk Model in the case of 30m sensing radius, as shown in Table 2.

Table 2: Average PDR and relative change of PDR of MsR2MRP with different sensing models and radii.

Radius	Sensing Model		
	Boolean Disk Model (PDR)	Linear Disk Model (Relative change)	Spatial Sensing Model (Relative change)
1 m	0.48	+1.13%	+1.03%
5 m	0.47	+0.38%	+0.97%
10 m	0.47	+0.54%	+1.32%
20 m	0.46	+1.41%	+2.73%
30 m	0.46	+1.50%	+3.38%

Subthesis III.2. *I proposed the enhancement of a novel wildfire model, which, as a result, evaluates the fuel moisture content of the fire-exposed area. Assessing the moisture attribute of an area provides a more realistic wildfire propagation, which can be utilized to efficiently plan and deploy WSN networks in a certain geographical location. By simulation measurements, I showed that the effect of the model’s fuel moisture content parameter on burnt area is significant, with a high statistical confidence level. The obtained simulation results show that the parameter can alter the burnt area ratio up to 40%. I also showed that the enhanced wildfire model’s behavior is consistent with the measurement results obtained from real wildfires concerning fuel moisture.*

The wildfire model proposed by Alexandridis *et al.* [15] evaluates vegetation type, density, and wind parameters to calculate fire spread, whereas it does not consider fuel moisture. To achieve a more faithful simulation of wildfire spread, the modified wildfire model also evaluates fuel moisture content, denoted by the p_{moist} parameter. The amount of fuel moisture negatively influences fire spread, as shown by the results in Figure 11.

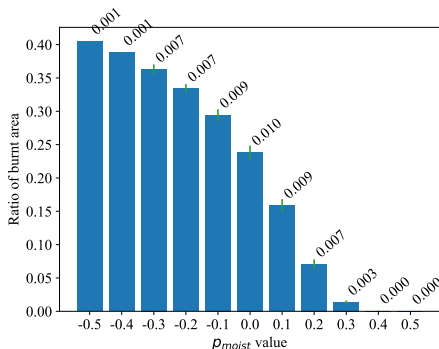


Figure 11: Effect of p_{moist} parameter on burnt area. Statistical confidence interval for 95% confidence level is provided for each parameter setting.

Furthermore, comparing the simulation results with the real-life measurements obtained by Rossa [30], shown in Figure 12, suggests that the behavior of the model is consistent with the phenomenon observed in a real environment. The p_{moist} parameter set to 0.4 corresponds to 120% fuel moisture content, whereas -0.5 can be matched to 20% content.

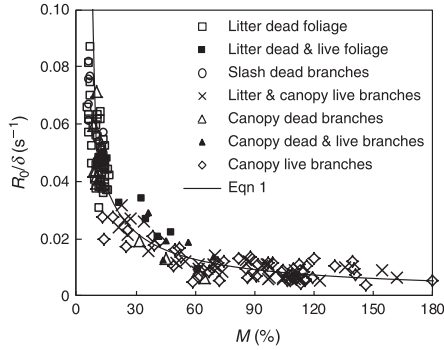


Figure 12: Ratio between basic fire spread rate and fuel bed height (R_0/δ) as a function of fuel complex foliar moisture content (M)[30].

Subthesis III.3. *I proposed the integration of models proposed in Subthesis III.1 and Subthesis III.2, which provides a realistic behavior of sensors that are exposed to heat transferred via gases, that is, convection. The proposed integration assesses the presence, direction, and velocity of air movement in conjunction with the present phenomenon to calculate the impact of the heat on the sensor. Based on simulation measurements, I showed that incorporating convection into the sensing model alters the sensor's reception in the upper quartile with 26%.*

Reviewed sensing models are phenomena indifferent and do not consider secondary effects of the environment. In the case of wildfires, the wind plays an important role in the direction and speed of the fire spread, but it also influences sensing due to the directed movement of hot air. To incorporate the effect of wind on fire sensing, an integration of the wildfire and the spatial sensing model was proposed, where the sensing is also influenced by the present wind. As illustrated in Figure 13, sensing values recorded in a WSN, where wildfire and wind are present, expanding towards the network show a significant difference, whether the effect of wind is considered in sensing or not. In particular, the difference in the upper quartile is important to mention, where the increase in the amount of the detected sensor readings is 26%. Environment-aware protocols and applications select threshold values from this region; the difference in sensed values has a direct effect on network behavior.

Subthesis III.4. *I proposed a probabilistic mobility model that resembles the relevant characteristics of limited mobility. The mobility model allows WSN nodes to perform locomotion with a pre-defined distance in a direction selected by stochastic means. The probability of the direction is influenced by the presence of neighboring nodes and hostile events. The model combines the inherent inaccuracies of limited mobility technologies with the results of utilizing information shared within sensor networks.*

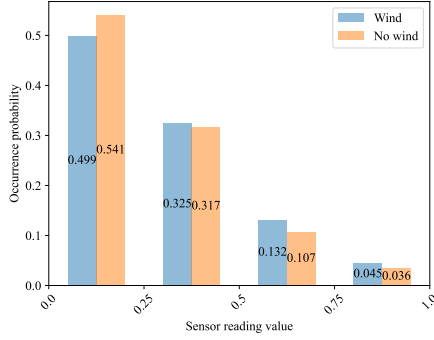


Figure 13: Non-zero sensed values of a WSN network in case of Spatial Sensing Model with and without wind information available.

Reviewed works on feasible locomotion solutions combined with the economic hardware available on a WSN node provide only limited precision. To model the behavior of such a solution with acceptable computational complexity, the limited mobility was proposed. As shown in Figure 14, the model allows locomotion of a fixed r_m distance. Furthermore, it is assumed that the WSN node travels the distance discontinuously and is able to assess its environment and recognize neighboring nodes and their relative distance based on information retrieved from the MAC layer. To maintain connectivity, but not to create a dense topology, the node performing locomotion prefers the vicinity of a single neighbor compared to a higher number of neighbors. However, since both the means of locomotion and sensing are limited in precision, the node's final destination is probabilistic, where the probability is influenced by the aforementioned factors.

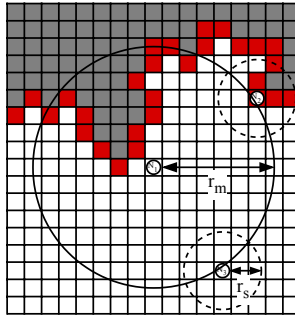


Figure 14: The mobility model and the cellular automaton's state. Cell color-state coding: red – burning, gray – burnt, white – not burning.

Subthesis III.5. *I proposed a metric that assesses the routing protocol’s capability related to multipath routing. The metric characterizes the overall disjointness of paths available in the network on a normalized scale. Furthermore, I proposed a metric to assess the monitoring performance of WSNs intended for monitoring spatially extent phenomena. The metric characterizes the WSN’s true potential to deliver information related to the monitored phenomenon. I compared both proposed metrics with contemporary, cognate metrics known from the literature. I showed that the proposed metrics provide extended scope and detail with regard to the investigated attribute, compared to the contemporary metrics.*

An important part of every WSN’s evaluation is the utilized metrics. Concerning network performance, the most commonly used metric is the Packet Delivery Ratio (PDR). The metric provides a ratio of messages sent and successfully delivered at the sink. Used as a network-level average, it is prone to outliers and does not reveal scarcity in node-sink connections. In WSNs, depending on the actual application, it is more important to receive information from as many nodes as possible within a predefined timeframe than the actual PDR of the network.

To assess the network’s coherence, a new metric, entitled Reachability, is proposed. The metric provides the ratio of nodes that successfully delivered a message to the sink and the total number of active nodes. The metric is time-dependent and does not provide throughput information.

In the case of multipath properties, a commonly used metric is the average number of paths available to a node. Whereas the metric provides a well-interpretable basis for comparison, it does not reveal any details on the paths. The proposed disjointness-score reveals the pairwise disjointness of available paths and provides insights into the redundancy of the paths. An overview of the different metrics is provided in Table 3.

6 Potential applications

My contribution to the body of knowledge presented in this dissertation bears various possibilities for potential applications. The proposed routing protocols, R2MRP [J2] and MsR2MRP [J3], are evaluated from various perspectives, enabling a deployment in a real-life environment. European Union (EU) funded projects, such as the SenForFire project [31], or the concluded FIRESENSE project [32], [33] already investigated low-cost WSNs for wildfire surveillance. In such an environment, the proposed protocols could be successfully deployed, evaluated, and based on the retrieved results, further enhanced. Products and services related to wildfire monitoring became available in various countries, such as Canada [34] or Germany [35]. The emerging offers by the private sector also signify the feasibility of the proposed methods.

Both proposed routing protocols, all benchmark protocols, the application, the employed sensing, mobility, and wildfire models are publicly available at the

Table 3: Proposed and reviewed metrics for multipath WSN. Proposed metrics are denoted with * character.

Name	Class	Description	Benefit	Limitation
Packet Delivery Ratio	Network performance	Average ratio of sent and received messages, measured at the sink.	Generally accepted performance metric.	Does not reveal node-level scarcity.
Distance-corrected Packet Delivery Ratio *	Network performance	Average of node-specific PDRs weighted with relative distance from the sink.	Indicates coverage-related performance.	Does not reveal node-level scarcity, hard to interpret.
Portion of living nodes	Network performance	Ratio of nodes that are in working state, able to monitor and route.	Indicates network health	Does not reveal messaging performance
Reachability *	Network performance	Ratio or number of nodes successfully delivering messages to the sink.	Reveals node-level scarcity.	Time-dependent, does not indicate throughput.
Average path number	Multipath	Average of available paths per node.	Easy to interpret.	Modest, does not provide details.
Disjointness-score *	Multipath	Ratio of pair-wise disjoint paths per node.	Reveals details on available paths.	Provides a relative value.

source code repository platform GitHub [36], and at the open research repository Zenodo [O1], [O2]. Publication of these assets not only enables the repeatability of presented results but also helps other academia and industry members evaluate their works in a common, accessible, and trustworthy simulation environment. Furthermore, the published source codes are an open call to the members of the scientific community to revisit the proposed protocols, enhance their capabilities, and provide new applications. Similarly, the proposed metrics can also help researchers focusing on routing protocols to evaluate and benchmark their work, especially in the field of multipath and multi-sink routing.

The presented TOPSIS-based load-balancing solution is reusable in multipath routing protocols, where various link, environment, energy, and network-related attributes are available during the network construction procedure or normal operation. Feasible candidates are the SMRP [19], LIEMRO [37], and ReInForM [38] protocols, where no, or just a limited load-balancing mechanism is available. In such protocols, the application of TOPSIS could enhance resiliency and energy efficiency. In contrast, ACO-based routing protocols, such as the E3AF [20], do not gain a significant advantage from such a mechanism, as the ACO algorithm’s pheromone concept fulfills a similar role.

The proposed application-driven mobility support for the MsR2MRP routing protocol is also reusable in routing protocols that fulfill the following criteria: a) each member of the network must preserve an interim state of the routing information prior to routing table construction, b) repeated routing table construction on reduced routing information must result in a loop-free network, c) there must exist an explicit messaging procedure to remove nodes performing mobility from affected nodes’ routing table and to trigger repeated information broadcast related to routing information. Protocols, such as SMRP, fulfill the aforementioned criteria and are capable of supporting mobility. In protocols, where routing table construction is a multi-step procedure, such as Directed Diffusion, the proposed approach may be complex or not feasible to implement. Furthermore, routing protocols that depend on scheduling and synchronization, such as LEACH, may also not be suitable to support the mechanism.

The majority of the works that investigate aspects of a WSN during event monitoring utilize simplified models as part of the simulation framework. The proposed models and their integration provide a framework that enables the trustworthy evaluation of routing protocols and applications. The spatial sensing model is suitable to model any measurable physical phenomena with spatial extent, be it steady in terms of intensity, such as an oil spill, or varying, such as a gas or wildfire. Incorporating the effect of the environment, specifically wind, on the sensing also facilitates a more faithful measurement of the phenomena. The proposed sensing models and the benchmark models are integrated and published with the measurement environment, providing a reusable platform to develop, evaluate, and benchmark environment-aware WSN protocols and applications.

Through this work, R2MRP and MsR2MRP were presented in the WSN

context; however, both protocols possess capabilities that enable them to be deployed in other environments. With the spread of IoT, numerous consumer and industrial networks are deployed, which require resilient communication. Whereas in the case of a WSN, impacting phenomena are physical, in certain networks, events, such as changes in the node's performance, radio conditions, or traversing traffic, can also be considered phenomena to which the network has to adapt. Recently, multipath-related techniques were adopted in different segments of the Internet protocol suite, such as the multipath extension of the Transmission Control Protocol (TCP) [39] or the Quick UDP Internet Connections (QUIC) protocol [40]. These extensions do not guarantee node-disjoint paths; however, the property could enhance connection resilience and provide advanced load-balancing capabilities.

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List of author publications

List of journal publications

- [J1] **B. Á. Üveges**, M. Lőrincz, and A. Oláh, “Resilient multipath routing protocol to enable hazardous event monitoring with wireless sensor network,” *Telfor Journal*, vol. 15, no. 1, pp. 20–25, 2023, ISSN: 2334-9905. DOI: 10.5937/telfor2301020q. [Online]. Available: <http://dx.doi.org/10.5937/telfor2301020q> (cit. on p. 5).
- [J2] **B. Á. Üveges** and A. Oláh, “Enhanced reliability in hazardous event detection: A resilient multipath routing protocol for wireless sensor networks,” *IET Wireless Sensor Systems*, vol. 14, no. 4, pp. 111–131, May 2024, ISSN: 2043-6394. DOI: 10.1049/wss2.12078. [Online]. Available: <http://dx.doi.org/10.1049/wss2.12078> (cit. on pp. 5, 7, 17).
- [J3] **B. Á. Üveges** and A. Oláh, “Resilient multi-sink, multipath routing for mobility-limited wireless sensor networks in hostile event monitoring,” *IEEE Access*, pp. 1–1, 2025, ISSN: 2169-3536. DOI: 10.1109/access.2025.3581731. [Online]. Available: <http://dx.doi.org/10.1109/ACCESS.2025.3581731> (cit. on pp. 5, 6, 8, 12, 17).

List of conference publications

- [C1] **B. Á. Üveges**, “Deploying wireless sensor networks: Effect of spatial topology on routing performance,” *PHD PROCEEDINGS ANNUAL ISSUES OF THE DOCTORAL SCHOOL FACULTY OF INFORMATION TECHNOLOGY AND BIONICS*, vol. vol. 19, p. 1, 2024, ISSN: 2064-7271. [Online]. Available: <https://m2.tmt.hu/api/publication/34903639> (cit. on p. 12).

List of other publications

- [O1] **B. Á. Üveges**, *Wireless sensor network based wildfire monitoring with application-specific multi-path routing*, 2024. DOI: 10.5281/ZENODO.10639881. [Online]. Available: <https://zenodo.org/doi/10.5281/zenodo.10639881> (cit. on pp. 5, 7, 19).
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